HYDRA: A New Paradigm for Astrophysical Modeling, Simulation, and Analysis

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What is HYDRA?

- **Descendant of XSPEC-style X-ray spectral analysis**
  Source models + Instrument models
  + Optimization + Visualization
- **Better data drives us toward more complicated sources, better visualization, distributed processing**
- **Not a data reduction package**
- **Complement to existing systems (CIAO, FTOOLS)**

$\Longrightarrow$ **A "toolkit" for simulation, modeling and analysis**

Why HYDRA?

- **Astrophysical sources are complicated!**
  - **spectral complexity**
  - **3D spatial structure**
  - **temporal variations**

- **Programmable, extensible analysis software can help**
  - **library of models for spatial, spectral, temporal structure**
  - **scriptable, enabling user-defined components**
  - **support for parallel processing** *(but not a requirement)*

Implementation

- **Building on the ISIS spectral analysis system**
  - *designed for X-ray spectral analysis*
  - *programmable, extensible spectral analysis system*
  - *embeds S-Lang interpreter*

- **Growing collection of modules**
  cfitsio, GSL, PVM, Gtk, HDF5, xpa, ...

- **Automatic module generation**
  SLIRP (C, C++, Fortran)

- **Targeted GUI applications**
  “GUI-lets”: VWhere, volview, evt2img

Source Models

Spectral models:

- **XSPEC model library**
- **user-defined via S-Lang or shared library**

Spatial Structure

Component-based approach:

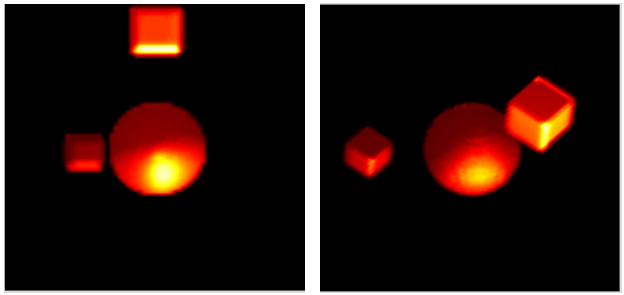
- `v3d`**: low-level 3D geometric components**
- `source3d`**: multiple 3D components with emission spectra**
- `event2d`**: Monte-Carlo model photons vs. event data**

Simulation-based approach:

- *e.g.* **HDF5 file input**
- **user-defined software**

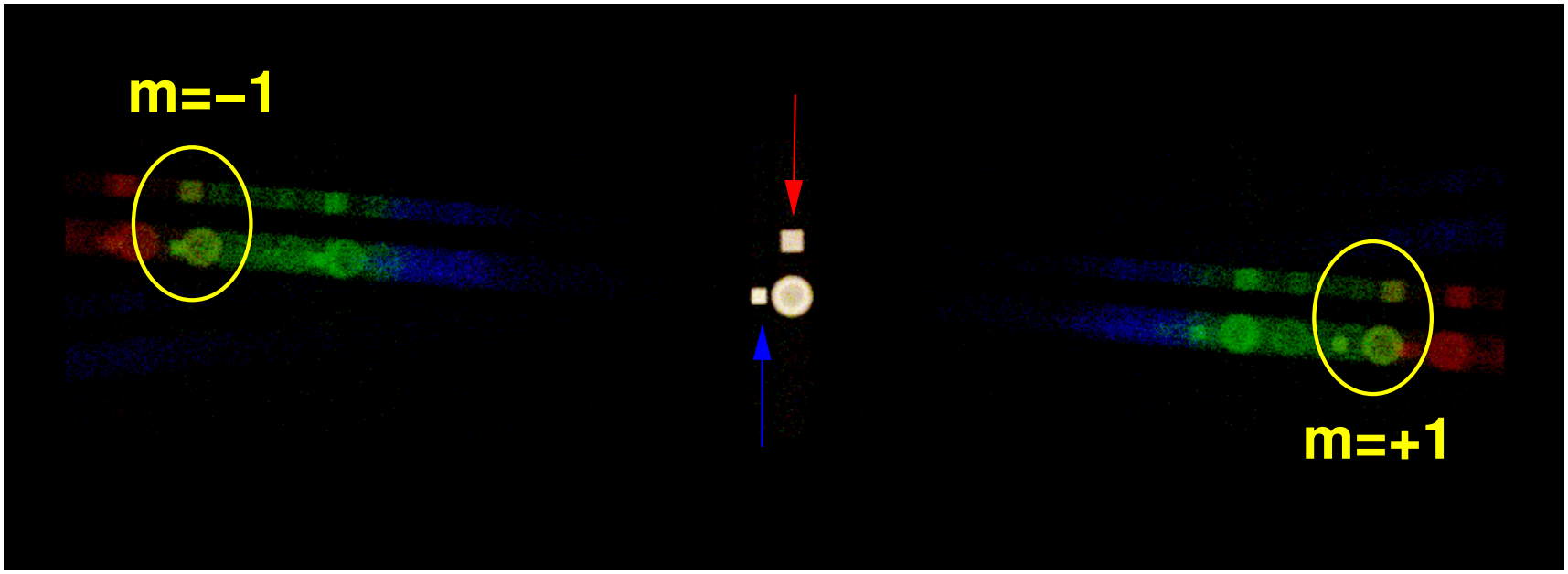
Example: Supernova Remnant

```
hydra> require ("v3d");
hydra> require ("volview");
hydra> v3d_setup(60.0,37);
hydra> x = v3d_sphere(12.0,18.0)
           + v3d_cube(9.0,[50.,0.0,-30.] )
           + 2.0*v3d_cube(6.0,[0.,30.0,30.]);
hydra> volview(x);
```



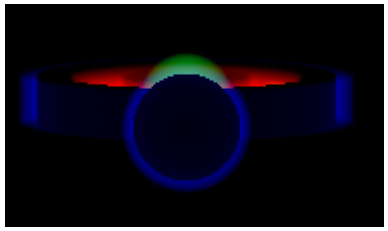
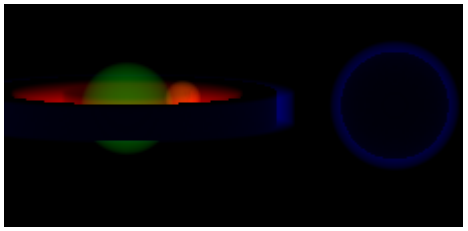
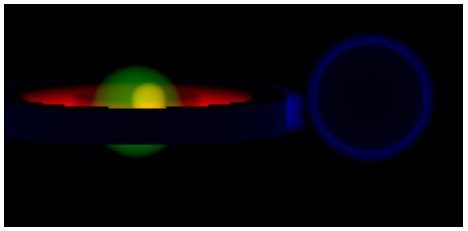
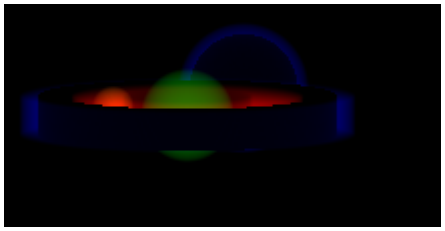
(cubes are for illustration only...)

Radial expansion, $v \propto R \implies$ *Doppler shifts*



color-coded photon energies using `evt2img`

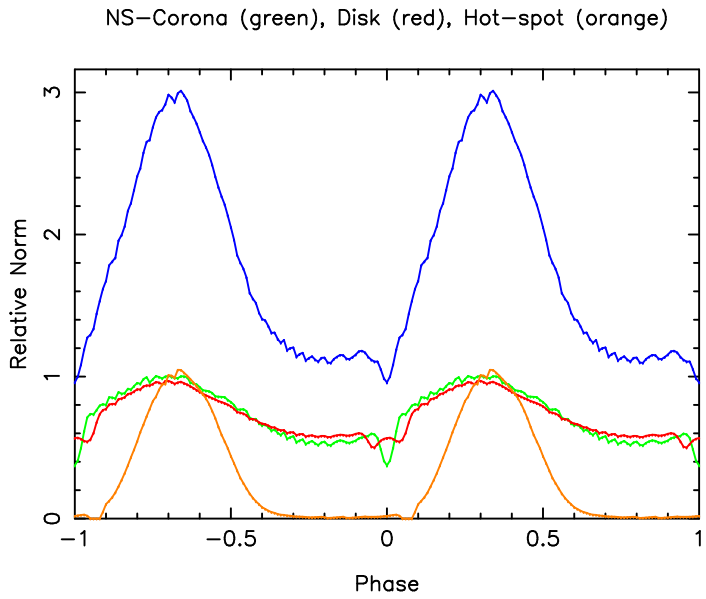
Example: Neutron Star + Accretion Disk

phase = 0 *0.25* *0.31* *0.44*

Five model components:

- **3 optically-thin emission components:**
  NS corona; Disk; Hot Spot
- **2 opaque components:**
  Companion star and disk rim




```
v3d_sphere(...) + v3d_cylinder(...) + v3d_sphere(...)

     + v3d_roche(...) + v3d_cylinder(...)
```

Model Fitting and Optimization

- **Export interfaces that separate optimization from model definition and data management.**

  $\Longrightarrow$ *Generic optimization and parameter management*

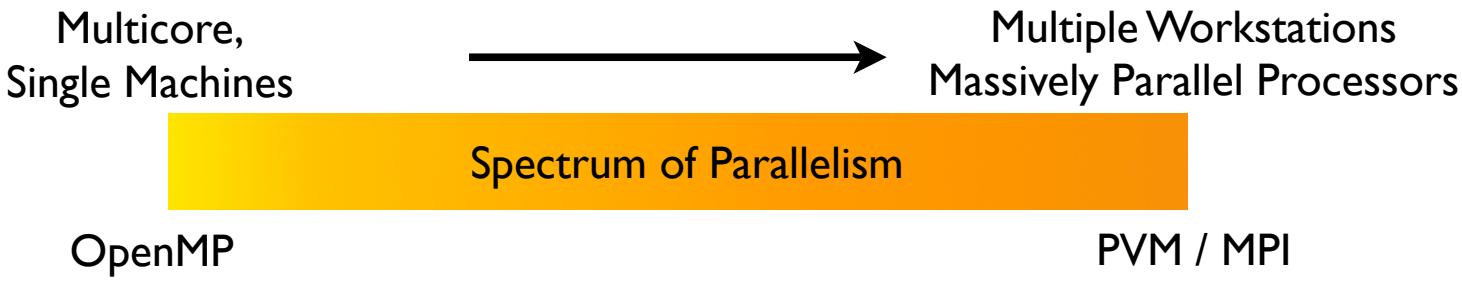
```
define model_comp1 (pars, metadata) {
   ...
   return value;
}
s = new_slang_function ("m1", &model_comp1, num_pars);
s.param_names = ["a", "b", "c"];
register_slang_function (s);

function ("m1(1) + m1(2) + foo(1)");
function_data (metadata);

minimize ();
```

- **Enable parallel processing at several levels**
  primarily through S-Lang interpreter, via PVM module

AIM: Parallelism In Standard Astrophysical Analysis



HYDRA prototype (ISIS) first to demonstrate this range of parallelism on standard problems in X-Ray spectroscopy:

Model Fitting
Confidence limits
Temperature Mapping
Emission Spectra of Photoionized Plasmas

Focal point for nurturing multiple, international collaborations in high-performance astrophysical computing (see publications).

AIM: Highly-Configurable Analysis

Standard X-Ray Spectroscopy Tools > 20 years old

Archaic *File In* ⟶ *File Out* Data Management Model

No matrix-oriented numerical capabilities

Context-sensitive visualization, limited to 2D model plots

Difficult to script & customize/adapt to new goals

HYDRA : Ground-up modular/scriptable/numerical

Example: 3D viz & OpenMP / PVM via extension modules
zero rewrite of application internals

Example: Atomic rates module auto-generated with SLIRP,
allowing important legacy Fortran command line app (XSTAR)
to be called as a function within HYDRA interpreter

See *Beyond XSPEC* paper (Noble & Nowak, 2008)

Development Plans

- **Generalize optimizer interface**
- **Explore opportunities for distributed computation**
- **Simplify model specification**
- **Improve component integration**

http://space.mit.edu/hydra/

2008 Publications and Abstracts

Chandra HETG Spectra of SN1987A at 20 years D. Dewey, S.A. Zhekov, R. McCray, C.R. Canizares Astrophysical Journal, 676, L131

Getting More From Your Multicore: Exploiting OpenMP From An Open Source Numerical Scripting Language M. Noble, Accepted, Concurrency and Computation: Practice and Experience

Beyond XSPEC: Towards Highly Configurable Astrophysical Analysis M. Noble, M. Nowak Submitted to Publications of the Astronomical Society of the Pacific

New Constraints on Jet/Disk Geometry and Radiative Processes In Stellar Black Holes XTE J1118+480 and GX 339-4 D. Maitra, S. Markoff, C. Brocksopp, M. Noble, M. Nowak, J. Wilms Submitted to Astrophysical Journal

Speeding Up Calculations of the Non-Equilibrium Ionization Model L. Ji, M. Noble, N.S. Schulz, M. Nowak, H.L. Marshall High Energy Astrophysics Division Meeting, April 2008, Los Angeles, CA